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Atmospheric, Solar, and CHOOZ neutrinos: a global three generation analysis

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We perform a global three generation analysis of the current solar and atmospheric evidence in favor of neutrino oscillations. We also include the negative results coming from CHOOZ to constrain the ν_e mixing. We study the zones of mass–mixing oscillations parameters compatible with all the data. It is shown that almost pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are required to explain the atmospheric neutrino anomaly and almost pure $\nu_1 \leftrightarrow \nu_2$ oscillations to account for the solar neutrino deficit.

1. Introduction

The evidence for non zero neutrino mass and mixing is, at present, the only solid experimental hint for physics beyond the Standard Model. Flavor oscillations [1] are the privileged tool to explore the neutrino mass and mixing parameter space. At present, there are three experimental indications in favor of neutrino flavor oscillations: 1) the evidence for ν_e appearance from a ν_μ beam in the Liquid Scintillator Neutrino Detector (LSND) [2]; 2) the evidence for ν_e disappearance in the solar neutrino flux [3]; 3) the strong evidence for ν_μ suppression in the atmospheric neutrino flux, together with the evidence of L–dependence of such suppression, in SuperKamiokande (SK) [4], as well as in MACRO and Soudan 2 [5].

Any of the above pieces of evidence requires a different mass scale: $\Delta m^2 \sim O(1\,\mathrm{eV}^2)$ for LSND, $\Delta m^2 \sim O(10^{-3}\,\mathrm{eV}^2)$ for atmospheric neutrinos, and $\Delta m^2 \leq 10^{-4}\,\mathrm{eV}^2$ for solar neutrinos. To account for all of them we need at least one sterile neutrino. Anyway, the evidence coming from LSND is, at the moment, controversial. For this reason, waiting for an independent confirmation of the LSND result, we prefer to discard this datum and to analyze only the solar and atmospheric evidence of oscillation in a "standard" scenario with three active neutrinos. In addition, we consider also the negative evidence coming from CHOOZ [6]. Such 1 km–baseline reactor experiment has not found any evidence for ν_e disappearance. As we will see, this negative result has a strong impact in constraining the 3ν parameter space. (Similar conclusions have also been derived by Gonzales–Garcia *et al.* [7])

2. The standard 3ν framework

Flavor eigenstates are related to mass eigenstates through the mixing matrix U:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i, , \qquad (1)$$

where $\alpha = e, \mu, \tau$. We stick in the "one mass scale dominance hypothesis", i.e., $\delta m^2 \equiv m_2^2 - m_1^2 \ll m^2 \equiv |m_3^2 - m_{1,2}^2|$. In this hypothesis – that will be proved *a posteriori* – CP violating effects are unobservable and the matrix elements $U_{\alpha i}$ can be considered, without loss of generality, real. Moreover, atmospheric (and, eventually, CHOOZ) neutrino oscillations probe the flavor composition of the "lone" state ν_3 and can be described by the subspace $(m^2, U_{e3}, U_{\mu 3}, U_{\tau 3})$. Conversely, solar neutrino oscillations can probe the mass composition of the ν_e and can be described by the subspace $(\delta m^2, U_{e1}, U_{e2}, U_{e3})$. The only common parameter that can be probed both by solar and atmospheric neutrino oscillations is U_{e3}.

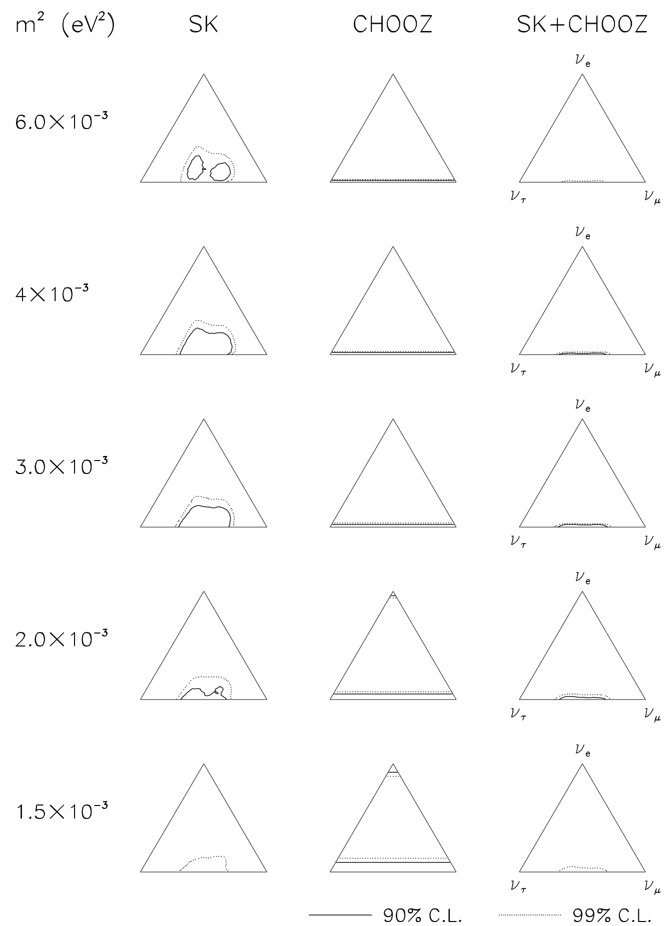

Figure 1. Allowed zones at 90% (99%) C.L. of SK atmospheric data (first column), CHOOZ (second column) and combined.

3. 3ν Atmospheric and CHOOZ analysis

We have performed an updated analysis [8] of the latest (70.5 kTy) data from SK [4] and CHOOZ [6]. The details of the analysis can be found in [9]. The SK data include 55 zenith bins: 10+10 bins for the subGeV e+μ events, 10+10 bins for the multiGeV e+μ events, and 5+10 bins for the upward stopping (US) and through-going μ events. For CHOOZ, we use the 14 experimental bins.

The result of the analysis is shown in Fig. 1, where the unitarity triangle introduced in [10] has been used. A point inside each triangle in Fig. 1 represents a generic combination of the flavor eigenstates (for a fixed m^2), the mixing matrix elements U^2_{e3}, $U^2_{\mu 3}$, and $U^2_{\tau 3}$ being identified with the projected heights onto the ν_τ–ν_μ, ν_τ–ν_e, and ν_μ–ν_e "sides" respectively. Using a well known property of the triangles with equal sides, the unitarity relation $U^2_{e3} + U^2_{\mu 3} + U^2_{\tau 3} = 1$ is thus satisfied.

The triangles on the left of Fig. 1 show the zones allowed using SK atmospheric data only, for five representative values of m^2. The absence of ν_e distorsion in the atmospheric flux tends excludes pure $\nu_\mu \leftrightarrow \nu_e$ oscillations, although a moderate mixing of ν_e is still allowed by SK data. The best fit is reached for $m^2 \simeq 3\times10^{-3}$ eV^2 and pure maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing ($U^2_{\mu 3} \simeq U^2_{\tau 3} \simeq 1/2$ and $U^2_{e3} \simeq 0$).

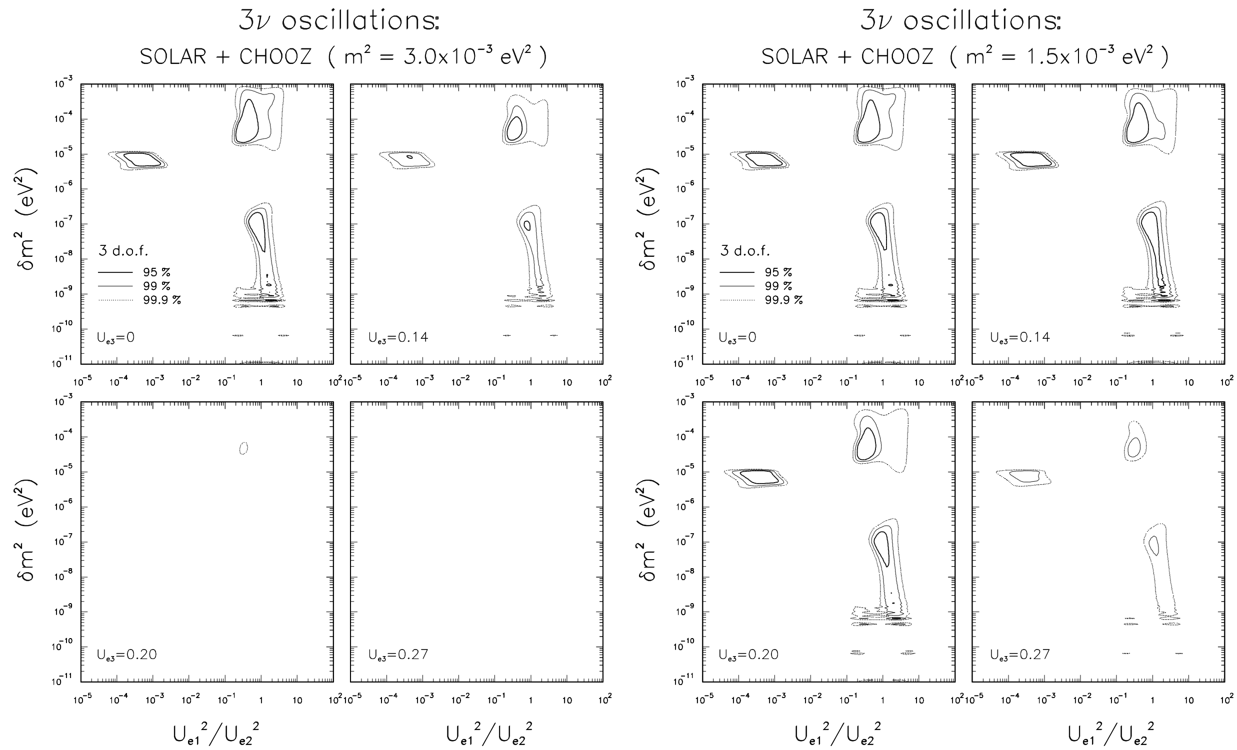

Figure 2. Allowed zones at 95%, 99% and 99.9% C.L. for the combination of all solar ν data and CHOOZ, for four representative values of U_{e3} and two representative values of m^2.

The middle column of triangles show the zones allowed by CHOOZ. In this experiment no signal of ν_e disappearance has been found. This is crucial in constraining the mixing between ν_3 and ν_e. The zones allowed by CHOOZ are shaped as horizontal strips near the bottom (corresponding to small values of U_{e3}^2) and near the ν_e corner (corresponding to $U_{e3}^2 \simeq 1$). The last solution is, however, incompatible both with solar and atmospheric neutrino oscillations.

The triangles on the right show the combined SK+CHOOZ analysis. Only a very small zone, around pure maximal $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, is allowed. Solutions disappear at 99% C.L. for $m^2 \geq 6 \times 10^{-3}$ eV^2 and $m^2 \leq 1.5 \times 10^{-3}$ eV^2. The best fit is reached again for $m^2 \simeq 3 \times 10^{-3}$ eV^2 and pure maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing. In particular, the upper limit on U_{e3} is $\simeq 0.3$ at 99% C.L.

4. 3ν Solar and CHOOZ analysis

In this Section we present an updated analysis [11] of the solar neutrino data (total rates and SK Day and Night recoil spectrum, as presented at the *Neutrino 2000* conference [12]), as well as of the latest theoretical solar ν fluxes and uncertainties [13]. The details of the analysis can be found in [14]. Moreover, we have included the CHOOZ constraints on U_{e3}. In this case, it is necessary to fix the value of m^2, since the leading oscillations in CHOOZ are driven by the higher mass gap (m^2).

In Figure 2 we show the results of the analysis for $m^2 = 3 \times 10^{-3}$ and 1.5×10^{-3} eV^2 (corresponding, respectively, to the best fit and to the lowest value allowed by atmospheric ν oscillations), and for increasing values of U_{e3}. The case $U_{e3} = 0$ corresponds to the usual 2ν analy-

sis, with the identification $U_{e1}^2/U_{e2}^2 \equiv \tan^2\theta$. The best fit is reached for $U_{e3}=0$, $U_{e1}^2/U_{e2}^2 \simeq 0.36$, and $\delta m^2 \simeq 4.7\times10^{-5}$ eV^2. The solution at small mixing angle is disfavored by the lack of the evidence of distorsion in the SK spectrum. Solar neutrinos alone prefer $U_{e3}=0$, although the upper limit on U_{e3} is weak ($U_{e3} \leq 0.8$ [14]).

For increasing values of U_{e3} the solutions rapidly disappear because they become incompatible with CHOOZ. In particular, the upper limit at 99% C.L. on U_{e3} is $\simeq 0.3$ for $m^2 = 1.5\times10^{-3}$ eV^2. The inclusion of CHOOZ in the analysis also strongly constrain the upper value of δm^2: $\delta m^2 \leq 7\times10^{-4}$ eV^2 at 99% C.L. For such high values of δm^2 the one mass scale dominance is valid only approximatively. For this reasons the subleading effects of nonzero δm^2 in CHOOZ and finite m^2 in solar analysis have been taken into account in the analysis.

5. Conclusions

We have presented an updated 3ν analysis of the atmospheric neutrino anomaly and the solar neutrino deficit together with the negative evidence coming from CHOOZ. Atmospheric neutrinos prefer almost pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with large mixing between ν_μ and ν_τ and $m^2 \in [1.5, 6]\times10^{-3}$ eV^2. In particular, the best fit is reached for maximal pure ν_μ–ν_τ mixing. Solar neutrinos still allow a multiplicity of solutions (with $\delta m^2 \leq 7\times10^{-4}$ eV^2), although large ν_1–ν_2 mixing is preferred. The combined analysis with CHOOZ strongly constrains the U_{e3} mixing ($U_{e3} \leq 0.3$). In particular, a theoretical attractive scenario, called "bimaximal mixing" ($U_{e1}^2 = U_{e2}^2 = 1/2 = U_{\mu3}^2 = U_{\tau3}^2$, $U_{e3}^2 = 0$) [15] is allowed. The goal for the next generations of experiments is to constrain more tightly the parameter space(s) and eventually to check (or disprove) non–standard solutions of the current evidences of neutrino oscillations.

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